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SUMMARY

The applicability of gaseous-film cooling to a rocket motor was investigated using a small JP-4 - gaseous-oxygen rocket motor. Data obtained from this investigation indicate that in the cylindrical portion of the rocket combustion chamber the Hatch-Papell gaseous-film-cooling correlation is directly applicable with purely convective wall heating and with a nonreactive, nondecomposable coolant gas. Even in the accelerating-flow field of the convergent and throat regions of the nozzle the correlation may be used, although it seems necessary to use a heat-transfer coefficient somewhat higher than that at the injection point. The data also indicate, though they do not positively prove, the necessity of including the effect of radiant heat transfer in gaseous-film-cooling calculations if this effect is of appreciable magnitude. Analysis of the data has indicated a simple empirical method by which the radiant heat transfer can be included in the correlation, although the actual numerical results presented can only be considered as a function of the particular motor geometry and flow conditions used in this investigation. It has also been shown that a reactive coolant gas may be used, although at the possible expense of a required flow somewhat higher than would be predicted for a nonreacting coolant with equivalent transport properties.

INTRODUCTION

The high wall heat flux encountered in modern chemical rocket motors and in advanced nuclear rocket motors presents a formidable challenge to the design team that is charged with the task of providing an engine that will maintain its structural integrity for a specified period of time. Numerous schemes have been proposed to eliminate or to alleviate the problem. Among these are regenerative cooling, transpiration cooling, heat-sink walls, refractory coatings, walls of high-melting-point metal, radiation cooling, ablation cooling, liquid- and gaseous-film cooling, and many others as well as combinations of the various methods. Each scheme has demonstrated varying degrees of usefulness depending upon the specific problem to be met, and each requires considerable knowledge of individual limitations and feasibility. The designer must also know the basic parameters and the proper manner in which to manipulate and apply them. Unfortunately, for many of the schemes such information is quite limited, especially in the new regimes encountered with higher chamber pressures and temperatures, new propellant combinations, etc. The present investigation was made in an effort to increase the usable knowledge of one of these schemes, gaseous-film cooling, as applied directly to a rocket motor.

Gaseous-film cooling is considered to have potential usefulness in three types of rocket motors: large solid-propellant motors, nuclear rockets, and high-energy liquid chemical rockets. The method shows promise for the large solid-propellant motors because it could allow the use of considerably lighter nozzle assemblies than the heat-sink type with heavy refractory-metal inserts at the throat that are currently being used. For gaseous-film cooling, however, the added complexity and weight of coolant tankage and flow systems must be balanced against the relative simplicity of the heavy heat-sink and refractory nozzles. Only a system and mission analysis could determine the better system for a given application. The case for film cooling in nuclear rocket motors, however, is more clear-cut. These motors are characterized by extremely high heat fluxes, particularly in the nozzle-throat region. Convective cooling using the propellant hydrogen as the coolant is desired. This cooling technique is limited, however, by the attainable coolant-side heat-transfer coefficients. A method is needed to decrease the heat flux that is actually transmitted to the wall, and the second-fluid-injection schemes, film and transpiration cooling, may be called upon to effect this decrease. Possibly some of the hydrogen could be bled off before entering the reactor, or a separate hydrogen supply could be used to provide the coolant. The high-energy liquid chemical rocket, using, for example, hydrogen and oxygen at high combustion pressure, presents essentially the same problem, and there is the same possibility of solution by film cooling. If film cooling is used, and if the film is liquid, considerable information is available (e.g., ref. 1). If the coolant is supplied as a gas or used as a gas film after evaporation from the liquid state, then gaseous-film-cooling correlations are necessary for the design analyses.

Most attempts at correlating gaseous-film cooling or film heating data were limited to the relatively low values of stream velocity and temperature typically found in airplane wing deicing systems and turbojet engine exhaust-cones (e.g., refs. 2 and 3). These correlations were usually based on the equation presented in reference 2. Succeeding investigations added to the range of conditions. Attainment of a satisfactory correlation, however, was difficult because of variations in geometries tested and operating procedures.

The investigation reported in reference 4 extended the hot-gas range to a temperature of 1500° F and a velocity of 1000 feet per second. Reference 5 used the same data and those of reference 3 to present a correlation based on a new theoretical flow model using tangential injection. Even this correlation required several empirical corrections, but it satisfied the data obtained over a very wide range of flow conditions with two geometrically dissimilar test rigs at different establishments and with two coolants of widely varying physical properties. A subsequent report (ref. 6) presented further semiempirical corrections to be applied to the equation of reference 5 to correlate data obtained with coolant injection through angled slots and normal holes.

The present report covers an experimental investigation and subsequent analysis of the application of gaseous-film cooling directly to a rocket motor, and it presents the results in the form of the Hatch-Papell correlation of references 5 and 6. The hot-gas velocities encountered by the film at the injection point were in the range 600 to 700 feet per second, although, in flowing along the nozzle wall, the film met gas traveling at velocities over 3000 feet per second in the throat region. The hot-gas total temperature at the injection point was about 4760° R. This investigation included the effects of cooling a cylindrical portion of the combustion chamber with both tangential and inward-angled coolant injection and cooling the nozzle with tangential injection. In each configuration nitrogen was used as the coolant, and, in addition, some data were obtained with the cooled nozzle using propane as the coolant. Some effort was also made to isolate the effects of radiant heat transfer on the film-cooling process.

EXPERIMENTAL APPARATUS AND PROCEDURE

The rocket motor used for this investigation was designed to burn JP-4 fuel and gaseous oxygen at chamber pressures up to 500 pounds per square inch absolute with a corresponding maximum thrust of 3700 pounds. The propellant injector used had a total of 40 concentric-orifice elements (oxygen around fuel) arranged in three circular rows (fig. 1). Nozzle and chamber heat-transfer measurements had indicated that this injector gave a reasonably uniform circumferential distribution of wall heat flux. The combustion chamber was water cooled and had an internal coating of zirconium oxide. The nozzle could be any of several types: heat sink, thin wall, etc. The engine was designed to permit studies of wall heat transfer through the nozzle, and, thus, all other components were designed conservatively and ruggedly to provide maximum reliability.

This rocket motor was fired in a 10-foot-diameter altitude tank in which ambient pressure down to 1.4 pounds per square inch absolute could be maintained along with a flow of air up to 40 pounds per second past the motor to dilute, cool, and carry off the products of combustion. For each firing, the tank ambient pressure was set at a value very close to the nozzle-discharge static pressure of the combustion gases to minimize any effects of over- or underexpansion of these gases. A general view of the rocket motor and its associated hardware installed in the altitude tank is shown in figure 2.

The propellant flows to the motor were governed by a calibrated electronic control system that would vary the flows to maintain a preset mixture ratio and combustion-chamber pressure. This control varied the oxygen fire-valve opening in response to a chamber pressure signal, and then similarly varied the fuel flow to maintain the proper ratio of the two flows. In addition, this control would open the propellant fire valves slowly according to a preset ramp at the start of firing to provide a fairly gentle start with minimum overshoot of chamber pressure. An automatic program timer was used to maintain the proper timing and sequence of the various functions involved in the firing, such as purges before and after firing, torch ignition, activation of the automatic flow control, etc. In addition, various safety controls were provided to prevent or terminate firing if certain conditions of temperature, coolant flow, etc. did not exist.

An automatic digital potentiometer was used to record the required data on magnetic tape at the rate of 37.5 bits per second. A high-speed automatic computer converted and reduced the data to the desired form.

Two film-coolant injectors of different design were used in this investigation. Figure 3 shows the stainless-steel assembly that injected the coolant tangent to the wall surface. The disassembled view shows the zirconium oxide coating on the inner surface of the slot lip. This was necessary to prevent thermal destruction of this thin (0.040 to 0.060 in.) lip, which was exposed on one side to near-ambient-temperature coolant and on the other to the 4760° R combustion products. The same view also shows the 45 equispaced supports that maintain the designed slot height - in this case, 0.045 inch for use with the nitrogen coolant. A similar 0.008-inch-slot-height assembly was also made for use with the propane coolant. The inward-angled film coolant injector is shown in figure 4. It was built of copper and was designed to pass the flow at an angle of 30° from tangential to the chamber wall. This slot assembly had no supports to maintain slot height at the design value of 0.045 inch, as can be seen in the disassembled view, but did have a zirconium oxide coating on the surface exposed to the hot combustion gases. Considerable trouble was experienced with distortion of the unsupported lip on this slot assembly, which caused the coolant velocity to vary both circumferentially and temporally through the duration of a firing. Reliable data were obtained from only two firings before this coolant injector was replaced with the stainless-steel tangential injector.

The variation of hot-gas heat-transfer coefficient along the chamber and nozzle without film cooling is a necessary piece of information for the correlation. This was obtained by the thermal-plug transient-temperature technique using a series of copper rods spaced appropriately along a copper heat-sink chamber extension and a similar copper nozzle. A photograph of the motor equipped for these tests is shown in figure 5 along with a cross-sectional sketch. Figure 6 shows a sketch of a typical rod installation. This radial rod ideally permitted only one-dimensional heat transfer so that the heat flux along it could be determined from the time-temperature histories of the thermocouples embedded in it, as long as no heat flux was permitted out the cold end. The heat flux from the rod divided by the difference between the hot-gas recovery temperature and the wall temperature extrapolated from the thermocouple measurements along the rod yielded the desired coefficient. The hot-gas recovery temperature was evaluated by assuming equilibrium composition of the combustion products, and it was corrected for combustion efficiency based on the ratio of measured to theoretical specific impulse.

The so-called thin-wall spool (fig. 7), which was used for collection of adiabatic-wall film-cooling data in the cylindrical portion of the combustion chamber, was a rolled tube of 0.060-inch nickel sheet 6 inches long matching the chamber and slot assemblies in inside diameter. The heavy iron flanges were welded to the ends of the spool with minimum contact area to minimize heat conduction along the spool and out through the flanges. Instrumentation consisted of platinum - platinum-13-percent-rhodium thermocouples welded to the outside of the spool in three axial rows at 60° intervals and at 1/2-inch axial spacings. Temperatures measured at each axial station were circumferentially averaged in the calculations to minimize the analytical effects of circumferential distortions of heat flux, coolant flow or velocity, etc. At one axial station, a complete circumferential survey of wall temperatures was made at 60° intervals to provide a further check on uniformity.

The thin-wall nozzle (fig. 8) was similar to the spool, being spun of nickel to the desired nozzle contour with a thickness of approximately 0.06 inch and welded to a heavy steel flange. The nozzle was ended 1.4 inches downstream of the throat because calculations indicated that at that point the metal could be approaching destruction due to high temperature and internal pressure forces. Instrumentation was the same as used on the thin-wall spool with the axial spacing between thermocouples being 1/2 inch measured along the inner surface contour of the nozzle. Four axial rows of thermocouples were used at 60° intervals to obtain the average wall temperature at each axial station. Both this nozzle and the thin-wall spool were well insulated on the outside after instrumentation to enable as close an approach to adiabatic wall conditions as possible.

Firings of the rocket motor with film cooling were terminated after all the wall temperatures had essentially reached their adiabatic, or equilibrium, values. This required approximately 40 to 45 seconds in each case. All firings made for the film-cooling program were set at a chamber pressure of 60 pounds per square inch absolute and a stoichiometric mixture ratio. Minor variations from these conditions were not considered to have any significant effect on resulting data used in the analysis.

DISCUSSION OF CORRELATION EQUATION

The Hatch-Papell equation for gaseous-film cooling, as presented in references 5 and 6, is given as follows with the symbols defined in appendix A:

$$\ln \eta = \ln\left(\frac{T_g - T_w}{T_g - T_c}\right) = -\left(\frac{h_g L X}{\dot{w}_c c_{p,c}} - K\right)\left(\frac{S V_g}{\alpha_c}\right)^{1/8} f\left(\frac{V_g}{V_c}\right) + \ln \cos 0.8\, \beta_{eff}$$

where β_{eff} is in radians and

$$f\left(\frac{V_g}{V_c}\right) = 1 + 0.4 \tan^{-1}\left(\frac{V_g}{V_c} - 1\right) \qquad \text{for } \frac{V_g}{V_c} \geq 1.0$$

$$= \left(\frac{V_c}{V_g}\right)^{1.5\left(\frac{V_c}{V_g} - 1\right)} \qquad \text{for } \frac{V_g}{V_c} \leq 1.0$$

With only convective heat transfer, K = 0.04. This equation and its terms should be used in the manner in which they were derived. There must be no heat addition to the cooled wall; that is, T_w is the adiabatic value of wall temperature reached with film cooling. The heat-transfer coefficient is measured at the slot location without cooling, the velocities are computed at the slot location, and all the coolant properties are computed at the temperature and pressure of the coolant as it leaves the slot. For this investigation, the properties for nitrogen and propane gases were obtained from references 7 and 8, respectively.

The equation was derived for the case of cocurrent flows in a constant-area duct with no axial variation of hot-gas properties and velocity and with convection as the mechanism of heat transfer, radiation being considered negligible. This model is matched fairly well by the cylindrical portion of the combustion chamber unless there is radiant as well as convective heat transfer to the wall. In a small rocket motor with a luminous flame containing high percentages of carbon dioxide and water, the radiative portion of the total heat flux to the wall can become quite appreciable at low chamber pressure, as indicated in reference 9, and it may have to be considered in an analysis or design. Obviously, the nozzle of a rocket motor does not meet the specifications of the flow model from which the equation was developed, and trouble was expected in direct application of the equation to data obtained from such a cooled nozzle.

A sample calculation of the cooling effectiveness term with a range of adiabatic-wall temperatures was made to indicate the effectiveness range of interest to the designer of a rocket motor. The coolant temperature was assumed to be 70° F, and the hot-gas temperature was set at 5000° F - both reasonably typical values. The results, plotted in figure 9, indicate that, for wall temperatures in the 1000° to 2000° F range, effectiveness values will lie between approximately 0.8 and 0.6. This defines the approximate range of effectiveness over which a good correlation is desired between data and the equation. Accuracy of correlation far outside this range is not of extreme importance to present rocket motor design, although it would, of course, be desirable should new regimes of wall, hot-gas, or coolant-gas temperatures be met in the future.

PRESENTATION AND ANALYSIS OF EXPERIMENTAL DATA

Determination of Heat-Transfer Coefficients

The values of the heat-transfer coefficient necessary for the correlating equation were determined by the transient-temperature, thermal-plug technique of reference 10 in copper heat-sink versions of both the exhaust nozzle and the chamber extension, or spool (fig. 10). The value indicated for the chamber is an average of the six measurements along the 6-inch length of the chamber; very little axial variation was noted in the values, and it was not regular. Because of hot-gas leakage past several of the instrumented rods in the nozzle, insufficient data were obtained in the convergent portion of the nozzle to locate the curve definitely, and, thus, part of the curve is dashed.

Mention might also be made at this time of several firings that were made with nitrogen-film cooling on the copper spool in an attempt to correlate the resulting nonadiabatic data on the basis of the Hatch-Papell equation. Since a correlation was not possible, it appeared that a revision of the equation was necessary. A revision based on an alteration of the heat balance in the flow model to account for the nonadiabatic wall was attempted for the limited available data. That it was not successful was probably due, in part at least, to the highly transient nature of the heat transfer to the wall.

Film Cooling of Thin-Wall Spool

The thin-wall spool was used to collect data under adiabatic-wall conditions with gaseous nitrogen injected as the coolant at angles of 0° and 30° from tangential to the wall. During the first firing with the tangential coolant injector, an effort was made to determine if the presence of the slot-lip supports would disturb the efflux of coolant gas to the extent that circumferential gradients of wall temperature would exist; such gradients could either cause burnout or result in inaccurate measurements of the wall temperature. The existence of circumferential gradients was indicated by the surface discoloration patterns shown in the postfiring photograph of figure 11, although, at the axial location of a circumferential gradient measurement and after only 4.3 seconds of running, the maximum and minimum temperatures measured across one slot-passage width were 1161° and 1117° R - a difference of only 44° R. This was not considered sufficient to invalidate the subsequent data or to pose a burnout hazard.

The data obtained with the film-cooled thin-wall spool are presented in figure 12(a), where the heavy line represents the correlating equation. Direct application of the Hatch-Papell relation gave rather poor results from a correlation standpoint. The data indicate quite obviously, however, the desirability of injecting the coolant tangent to the wall. The approximate difference in effectiveness of 0.1 between comparable flows at any given distance from the slot could mean a difference of 400° to 500° F in wall temperature, which could easily mean the difference between success and failure of a design.

In an effort to determine the reason for the apparently poor correlation indicated in figure 12(a), an analysis was made of the possible effects of hot-gas radiation on the film-cooling model of references 5 and 6. The necessary modification to the model and subsequent data calculations are presented in appendix B. It was found that, if the supposed radiation correction is in fact necessary and if the proper approach has been taken, the data will fit the correlation with reasonable accuracy, as shown in figure 12(b) for 0° and 30° injection-angle data. The analysis indicated that the necessary alterations in the correlating equation would be a modification of the measured heat-transfer coefficient to include only the convective portion of the total and a decrease in the K term (even to a negative value as needed with the present data).

Figures 12(a) and (b) include some data that are questionable (tailed symbols). Gaseous-film-cooling data at great distances from the injection point tend to show a leveling-off effect (see ref. 5) for two reasons: (1) the tendency of the coolant gas to mix with the hot gas results in a lower bulk driving temperature than that which is used in calculating the effectiveness and (2) in this particular piece of hardware, the downstream end of the nickel spool is welded to a heavy iron flange, which can act as a heat-sink to lower the wall temperature at the hot end. The first reason could be especially valid in the present case, inasmuch as the total coolant flow is roughly 50 percent of the total hot-gas flow, and, with the considerable turbulent mixing expected, the resulting bulk driving temperature could easily be lowered a significant amount. This effect would be expected to be greater with angled injection because of consequent promotion of the mixing process. Such an effect is obvious in figure 12(a).

With an axial temperature gradient existing in the wall, and particularly with the steep gradient indicated by the present data, conduction of heat must occur axially in a direction opposite to the coolant flow. This tends to equalize the wall temperatures, and thus the data show a lesser negative slope than predicted by the correlation. This effect is shown by the tangential injection data of figure 12(a), although to a greater degree than might be expected from the axial-conduction mechanism alone.

During many of the firings with the tangential coolant injector, a thermocouple was embedded in the end of the slot lip to enable monitoring of the temperature of this critically heated location and to effect an automatic shutdown if a preset temperature was exceeded. Typical values of this temperature at various coolant flows were between 1100° and 1500° F. These values were sufficiently high to cause expansion of the lip outward against the lip supports; postfiring examinations showed impressions of these supports 0.0002 to 0.0003 inch deep in the lip. This certainly indicated that some form of support for the lip was necessary to avoid partial or total closure of the coolant slot during firing with obviously disastrous results. The postfiring examinations also indicated that the lip had shrunk in diameter after cooling because compressive stresses caused by thermal expansion of the restrained lip had exceeded the yield point of the metal. The resulting slot height was nearly twice the original height and the lip, of course, was unsupported. This meant that a new slot lip was necessary for each engine firing because a single experiment demonstrated that, if firing was attempted with the wider slot, the lowered coolant velocity caused poor cooling of the wall before thermal expansion of the lip could promote a more effective coolant flow pattern.

Film Cooling of Thin-Wall Nozzle

Data obtained from the gaseous-film-cooled thin-wall nozzle are presented in figure 13 for nitrogen and propane coolants. The heat-transfer coefficient used is the arithmetic average between that at the injection point and the peak value indicated in figure 10. This axially constant value was used, not for any analytically proper reason, but because it yielded the most consistently satisfactory results. No correction for radiation was made to the K and h_g values, and, as expected, the data obtained in the high-radiation zone near the nozzle entrance show the greatest shift to the left. Little or no shift is noted in the low-radiation region within about 1 inch of the throat. This effect is expected because the decreasing hot-gas static temperature through the nozzle has a fourth-power effect on the radiation to the wall. Both sets of data indicate a tendency toward increasing effectiveness past the nozzle throat, which is possibly due to supersonic flow effects that have not yet been incorporated in the correlating equation. This effect is not due to axial conduction to a heavy flange, as was probably the case with the spool data, inasmuch as there was no flange on the downstream end of the abbreviated nozzle (fig. 8).

It should be pointed out that the Hatch-Papell correlation was derived for flow in a constant-area duct, and nozzle flow certainly does not meet many of the original specifications. For example, the heat transfer is far from constant: the cooled width L (local circumference in a rocket motor chamber or nozzle) varies through the nozzle and in turn has an effect on the coolant-film thickness, which is also affected axially by the axial variations of hot-gas static pressure and coolant velocity; the coolant velocity variation in turn affects the velocity ratio. With all these axial variations taking place contrary to the original model for the correlation, it seems significantly fortuitous that the nozzle film-cooling data fit the correlation as well as they do without any inclusion of the variations in the calculations. Indeed, many trials of inclusion of these variations individually and in possible combinations yielded results obviously inferior to those presented. Evidently, compensating factors permitted the use of the correlating equation in its simple cylindrical-surface form.

With propane as a coolant, the evident correlation of data is even more significant for two reasons. First, as the propane gas is heated in passing along the wall, its specific heat varies considerably, which poses an additional strain on the conditions of the original derivation of the correlating equation. Second, propane is a reactive gas and could combine with any unconsumed oxygen that might happen near the coolant layer. This would not only impose a possible increase in the wall heat flux, but would also decrease the available coolant flow - both of which would affect the correlating equation. Figure 14 is a photograph of the nozzle from the downstream end, taken after a firing with propane as the film coolant, that shows deposition of carbon in axial streaks on the wall. The insulating effect of the carbon from the propane decomposition could affect the measured wall temperatures, but perhaps even more significant than this is the similarity in number of streaks, 20 at best measurement, and the number of propellant injector elements in the outer row, 20. This would indicate that some coolant-oxidant reaction was taking place, with the resulting adverse correlation effects already mentioned. An effect of a compensating nature is present with the propane gas. The decomposition that produced the carbon streaks is highly endothermal, which would tend to increase the effective specific heat and thereby add another axial variable to the already considerable list. Perhaps, the fact that the propane data are disposed toward somewhat lower values of effectiveness than the nitrogen data indicates that the degree of harm from reaction is somewhat greater than the degree of benefit from decomposition.

In order to ascertain the accuracy with which the data were taken and the reproducibility of the data with a given set of flow conditions, a check run was made at a later date to duplicate one particular firing with the nitrogen-cooled nozzle. The results of the two runs, with less than 0.3 percent error in setting of coolant flow, are presented in figure 15, and they indicate excellent reproducibility of axial cooling effectiveness gradients. The worst variation is only about 1.5 percent, the average being considerably less than 1 percent.

CONCLUDING REMARKS

The data obtained during this investigation indicate that, in the cylindrical portion of the rocket combustion chamber, the Hatch-Papell gaseous-film-cooling correlation seems to be directly applicable with purely convective wall heating (as determined by eliminating the supposed radiation effects present in these data) and a nonreactive, nondecomposable coolant gas. Even in the accelerating-flow field of the convergent and throat regions of the nozzle, the correlation may be used, although it was necessary to use an average heat-transfer coefficient between the maximum value and that at the injection point. The data also indicate, though they do not positively prove, the necessity of including the effect of radiant heat transfer in gaseous-film-cooling calculations if this effect is of appreciable magnitude. Analysis of the data has shown a simple, though somewhat empirical, method by which the radiant heat transfer can be included in the correlation, although the actual numerical results presented can only be considered applicable for the individual motor geometry and flow conditions tested. It has also been shown that a reactive coolant gas may be used, although at the possible expense of a coolant flow somewhat higher than ideal, if a reactant is present in the combustion products near the wall.

Examination of the correlating equation shows a strong effect of coolant-to-hot-gas velocity ratio on the wall-temperature distribution, and for this reason the slot heights used during this investigation were designed to provide a coolant velocity close to the hot-gas velocity at an expected average flow for each of the coolant gases. The obvious reason for this strong effect is the promotion of turbulent mixing due to velocity mismatching at the interface along with the consequent gradual erosion of the coolant film. If the coolant gas were to be injected in the convergent portion of the nozzle close to the throat, some trouble could be experienced in obtaining sufficiently high coolant velocity inasmuch as the hot-gas velocity becomes quite high as it approaches sonic flow at its high temperature, and the coolant would have a lower sonic velocity because of its low temperature. The obvious solution would be to use a coolant of lower molecular weight (and consequent higher sonic velocity) than that of the hot gas. The light gas has the additional advantage, of course, of higher specific heat - a fact that would undoubtedly be considered even without need for the sonic-velocity benefit. This sonic-velocity benefit of the light coolant gas would unfortunately not be available in a nuclear rocket that uses hydrogen as its propellant.

The film-cooling tests reported here used coolant flow rates as high as 42 percent of the total propellant-plus-coolant flow rate, obviously an undesirably high percentage for a flight engine. Two things must be noted, however. First, a flight film-cooling application would use a coolant gas possessing a lower molecular weight, a higher specific heat, and thus a lower weight requirement than the nitrogen and propane used here. For example, the change from nitrogen to hydrogen as the coolant gas would cut the flow requirement by a factor of about 14. Second, in a flight engine the chamber pressure would be much higher than the 60 pounds per square inch absolute of this engine, and while the propellant flow would increase directly as the combustion pressure increased, the convective wall heat-transfer coefficient and, thus, the coolant flow requirement would increase only as the propellant flow to approximately the 0.8 power. These two things combine to indicate coolant-to-propellant flow ratios of the order of 1 to 2 percent for typical flight engines.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 26, 1963

APPENDIX A

SYMBOLS

$c_{p,c}$ coolant specific heat

f function

h_g hot-gas heat-transfer coefficient

K constant; 0.04 with only convective heat transfer

L cooled width (slot circumference in cylindrical duct)

S coolant-slot height

T_c coolant temperature

T_g hot-gas recovery temperature (assumed to equal total temperature)

T_w wall temperature

V_c coolant velocity

V_g hot-gas velocity

$\dot{w}_c$ coolant flow rate

X distance downstream of coolant injection slot

α_c coolant thermal diffusivity

β coolant injection angle relative to wall

β_{eff} effective coolant injection angle, $\tan^{-1} \dfrac{\sin \beta}{\cos \beta + \dfrac{\rho_g V_g}{\rho_c V_c}}$

η cooling effectiveness, $\dfrac{T_g - T_w}{T_g - T_c}$

ρ_c coolant mass density

ρ_g hot-gas mass density

APPENDIX B

RADIANT HEAT-TRANSFER EFFECT ON GASEOUS-FILM COOLING

As shown in figure 16, direct application of the Hatch-Papell equation to the sample problem of cooling the present thin-wall spool with a nitrogen flow of 0.942 pound per second yields the result that the wall temperature does not start to rise up to a point about 0.08 foot from the injection point, because the coolant has moved this far during the time taken for heat to be conducted through the film to the wall. Beyond this point, the wall temperature rises rapidly. The measured axial variation of wall temperature, however, follows approximately the same indicated slope as predicted by the equation but at a much higher level - 900° to 950° F higher. This effect might be expected if radiant heat transfer were taking place along with the convective heat transfer, inasmuch as an axially nearly constant heat flux would be imposed on the wall that would result in an axially nearly constant increase in wall temperature.

An extrapolation of the data back to the coolant temperature, following approximately the predicted temperature slope, results in an intercept at a distance from the slot of about -0.1 foot. By the method of reference 5, this distance is equal to $K\dot{w}_c c_{p,c}/h_g L$, and a simple calculation would give the value of K to be used in the correlation, if the value of the convective heat-transfer coefficient h_g were known. A designer would, of course, be able to calculate both radiant and convective heat-transfer coefficients, and, assuming the supposed radiation correction on K was the only correction necessary, he would then only need a method for determining the wall temperature rise to be expected from the radiation in order to obtain the K value for the film-cooling correlation. In the present case, the problem is reversed. A method must be found to determine the radiant heat flux from the increment of wall temperature above that predicted by the original correlation; this must be used to lower the heat-transfer coefficient to the convective value, which will be used to calculate a new K that can be used in the correlation. Of course, the radiant heat flux calculated by this tenuous reverse method must be checked by more conventional direct methods.

The radiant heat flux was assumed to heat the wall directly, which in turn heated the coolant film by convection. The coolant-film temperature distribution was assumed to be the same as the predicted wall-temperature distribution of figure 16, and the familiar Dittus-Boelter relation was used to calculate an effective wall-to-film convective heat-transfer coefficient at a distance from the slot of 0.15 foot (about the middle of the range of good data) by assuming that the combustion chamber was flowing full of nitrogen coolant gas at the film temperature at this location. Properties were based on an average between film and wall temperatures. The resulting effective heat-transfer coefficient times the difference between wall and film temperatures yields an approximated radiant heat flux that is 30 percent of the measured total wall heat flux.

In order to check this value, the methods of Hottel and Egbert (as expanded in ref. 9) and reference 11 were used to calculate the radiation from the hot gaseous water and carbon dioxide. Resulting values were about 6 and 8 percent, respectively, of the total measured heat flux. At first glance, the comparison with the fictitious value of 30 percent seems poor, but reference 12 indicates that hydrocarbon flames with incomplete combustion can have radiant power equal to 2 to 10 times their gas-phase radiation, because of luminous particles, and, while the propellant mixture ratio in the present tests was essentially stoichiometric, certainly combustion must have been incomplete to some degree. For this reason, the approximated value of radiation is assumed to be reasonably accurate, which results in the convective heat-transfer coefficient being reduced by 30 percent to 0.0407. From this value K is calculated to be -0.020. Average values for h_g and K for the four sets of data are 0.042 and -0.017, respectively. Numerically, these values apply only to the present case and could not, of course, be applied to another case.

A designer, in using this method, would assume coolant flow conditions, calculate the radiation to be expected, and then use the empirical method to find the average wall-to-film temperature difference. He could then simply add this to his predicted nonradiation wall-temperature curve, use it to calculate a new K, and then use the resulting equation to obtain the final wall-temperature distribution. Iteration would be necessary to obtain proper values of slot height and coolant flow to satisfy continuity and the design temperature requirements.

It must be noted that, while flame radiation has been the only force considered to affect the present data in this discussion, other effects must certainly have contributed to the original lack of correlation. They have conveniently been included in the single "radiation" correction. The designer would possibly have to make empirical adjustments to his calculation of the effect of radiant heat transfer in order to be somewhat conservative in the wall-temperature calculations.

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Figure 1. - Propellant injector.

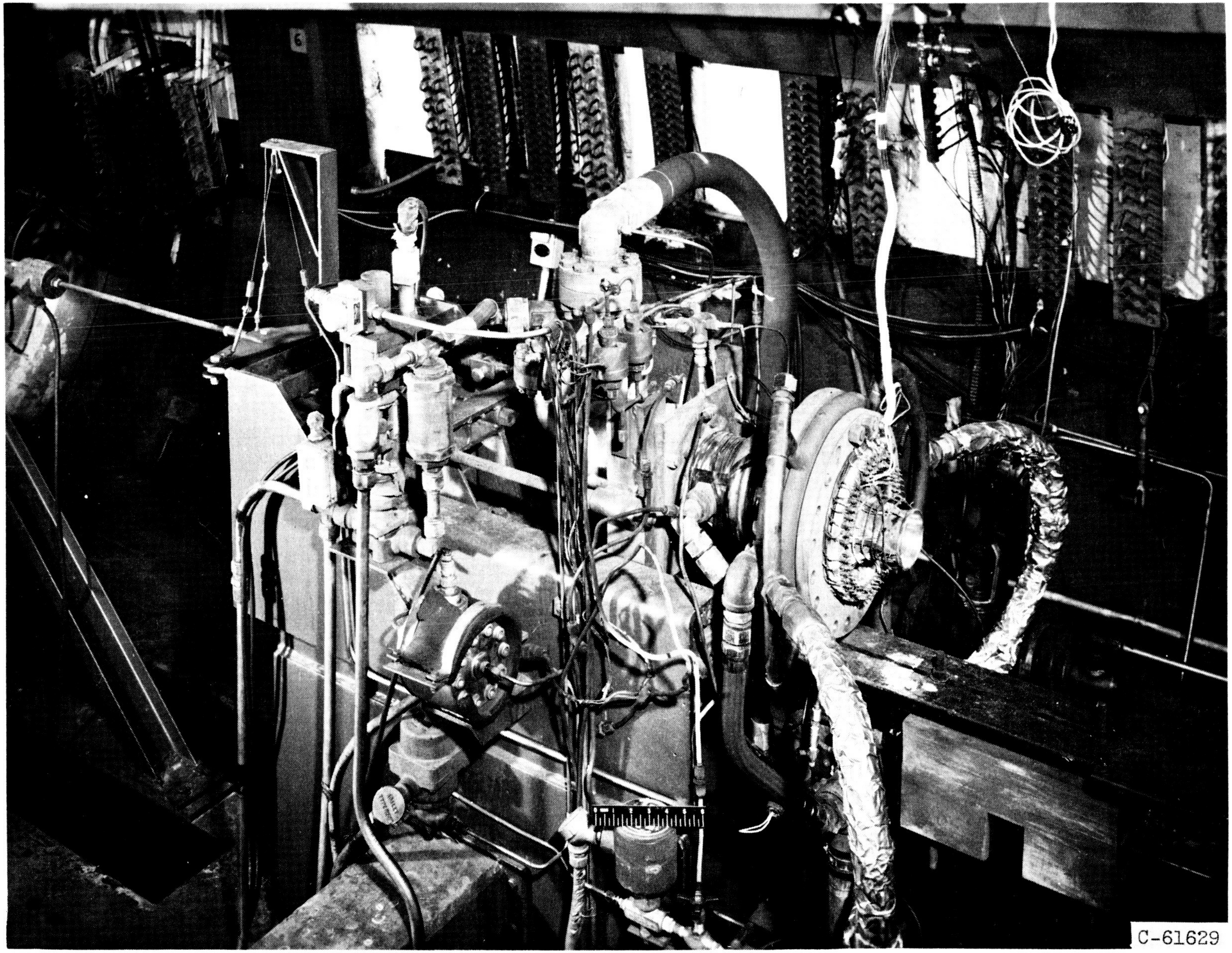


Figure 2. - Rocket motor installed in test facility.

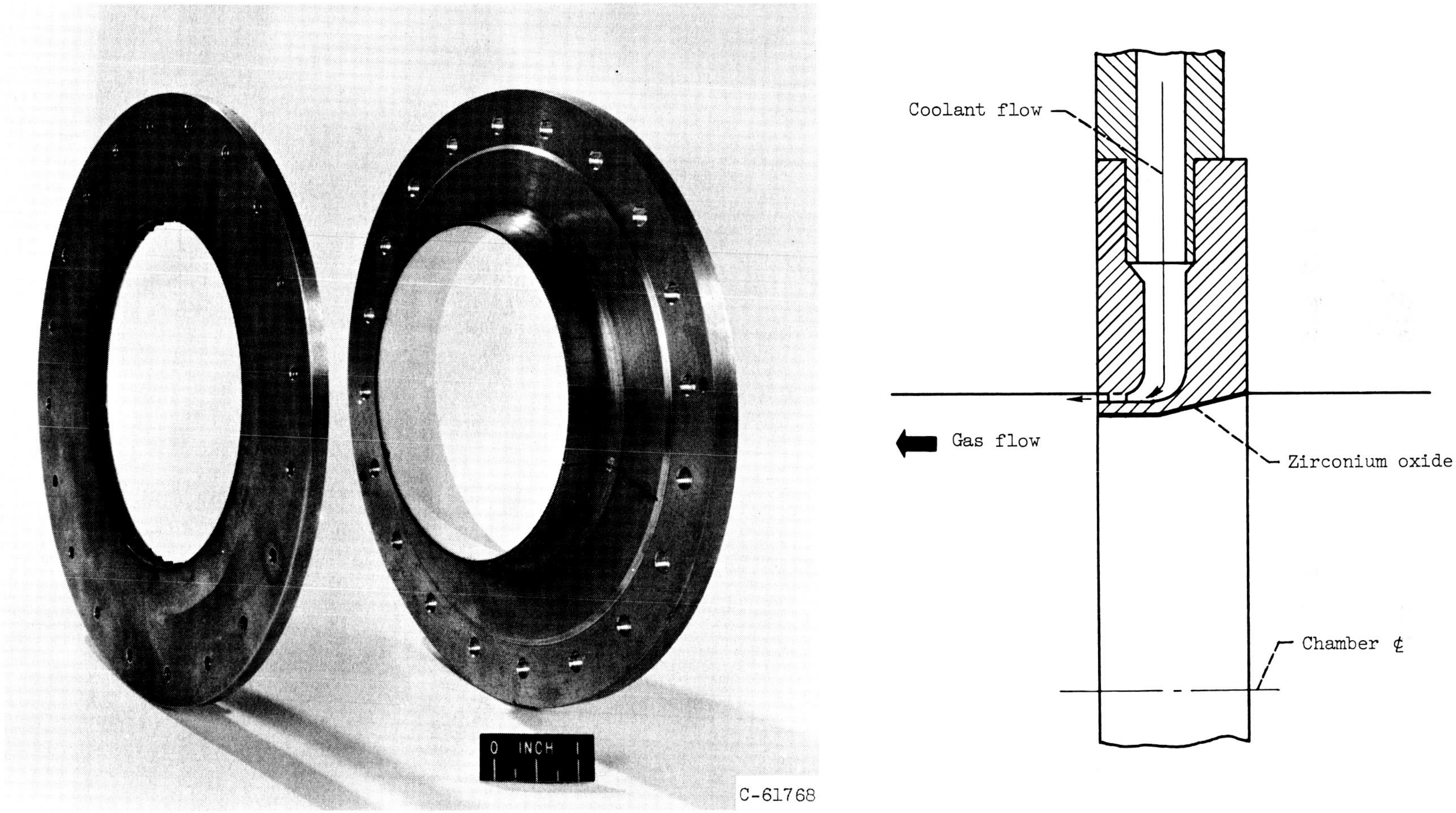


Figure 3. - Stainless-steel tangential-injection coolant-slot elements.

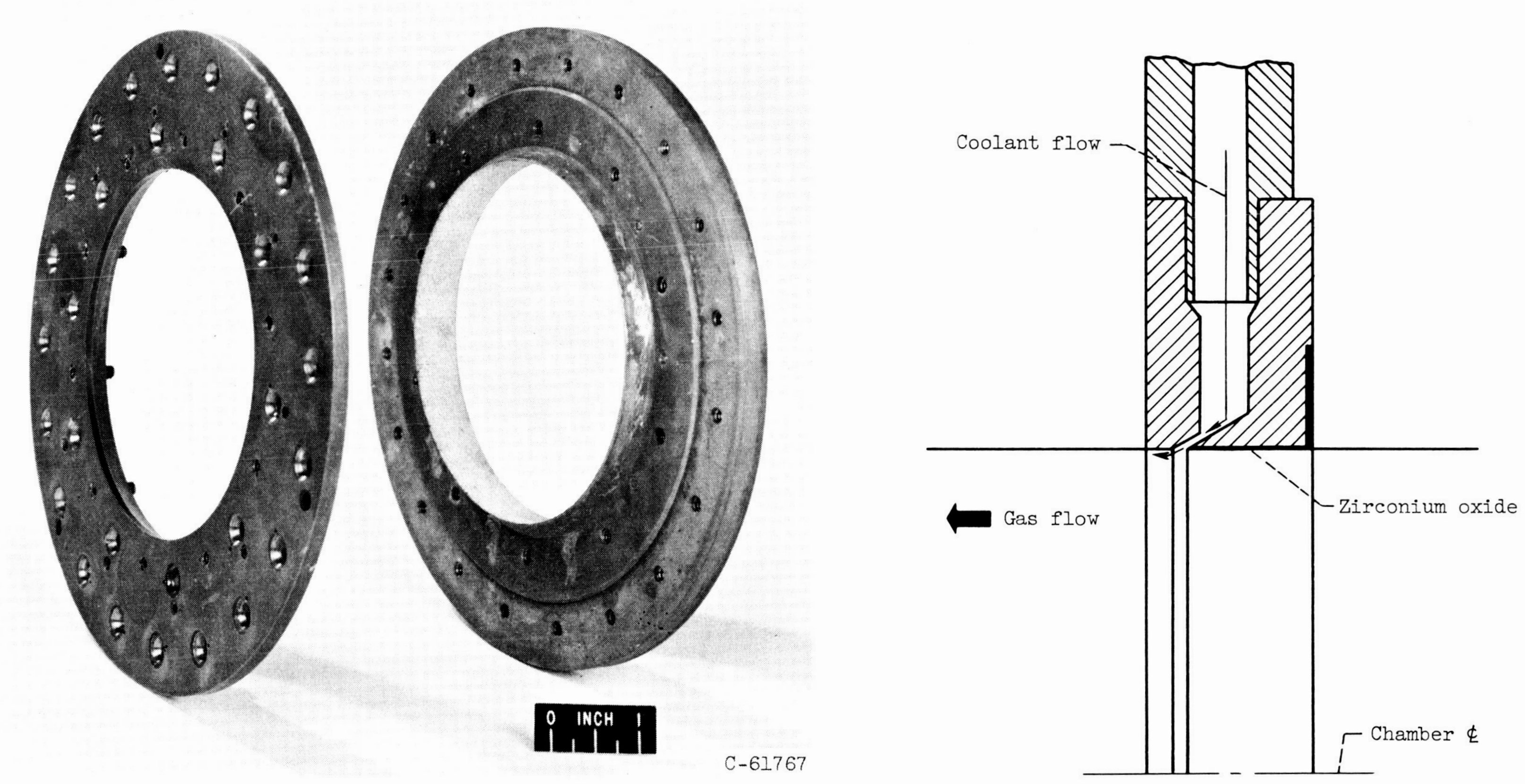


Figure 4. - Copper 30° injection coolant-slot elements.

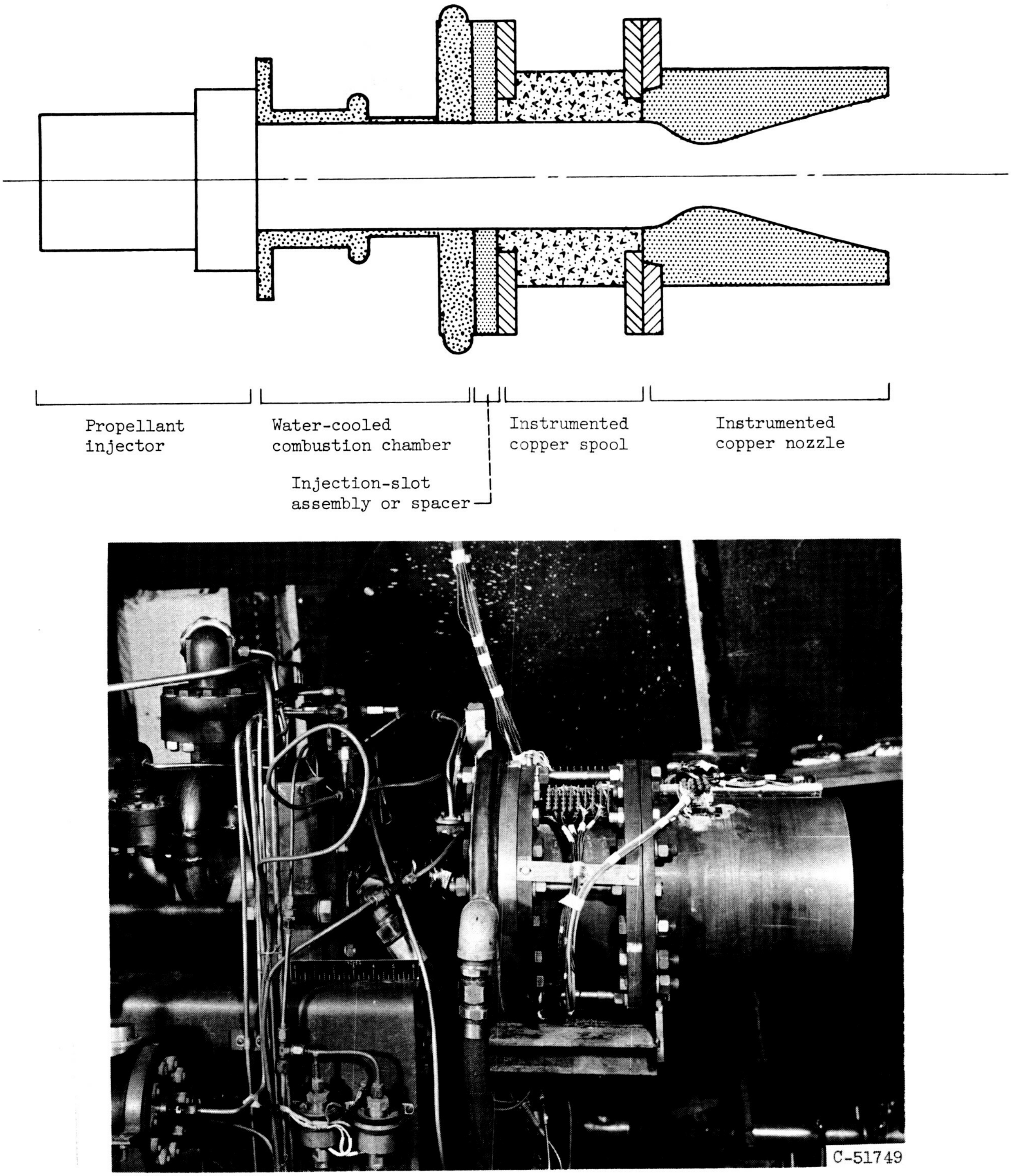


Figure 5. - Engine configuration for chamber heat-transfer tests.

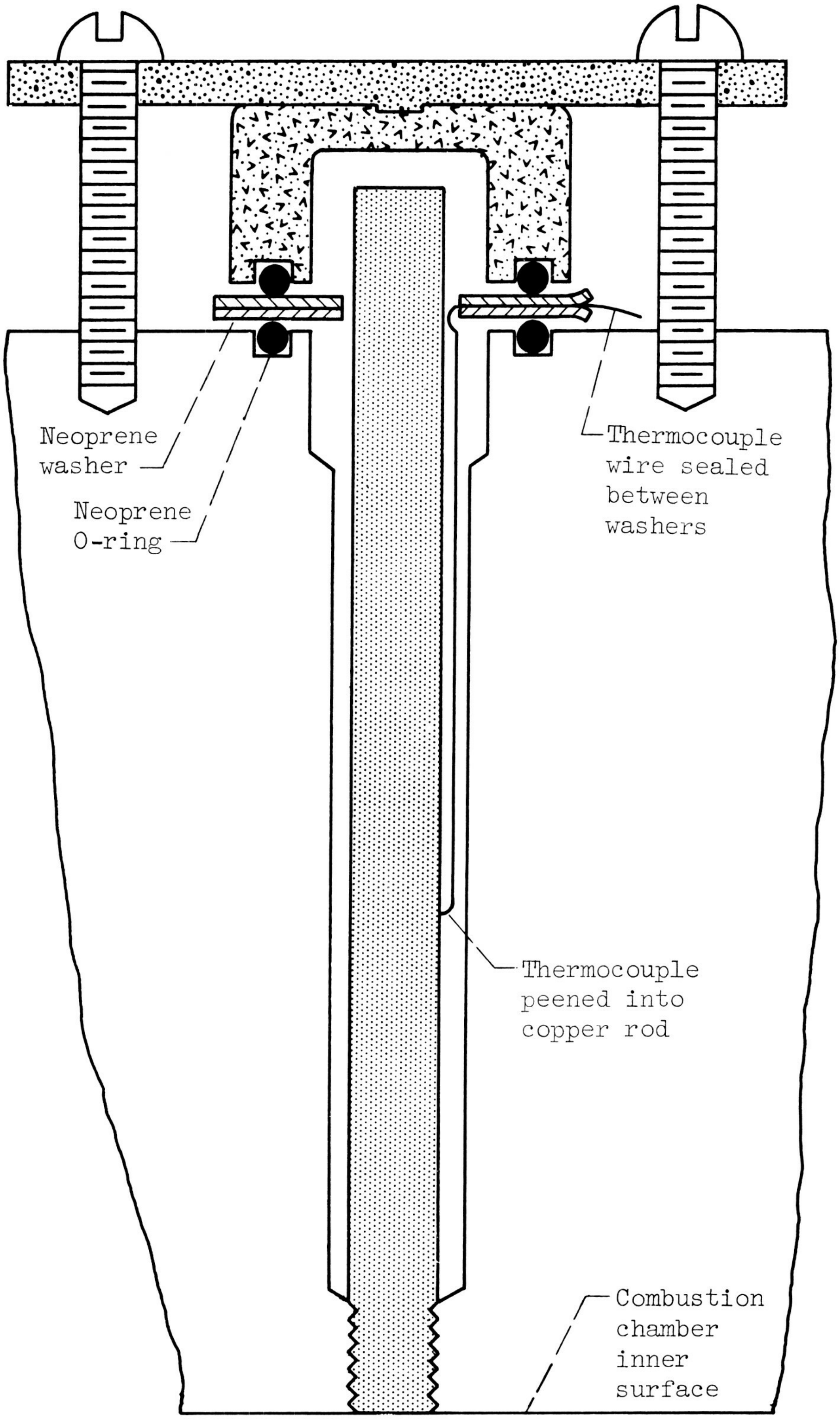
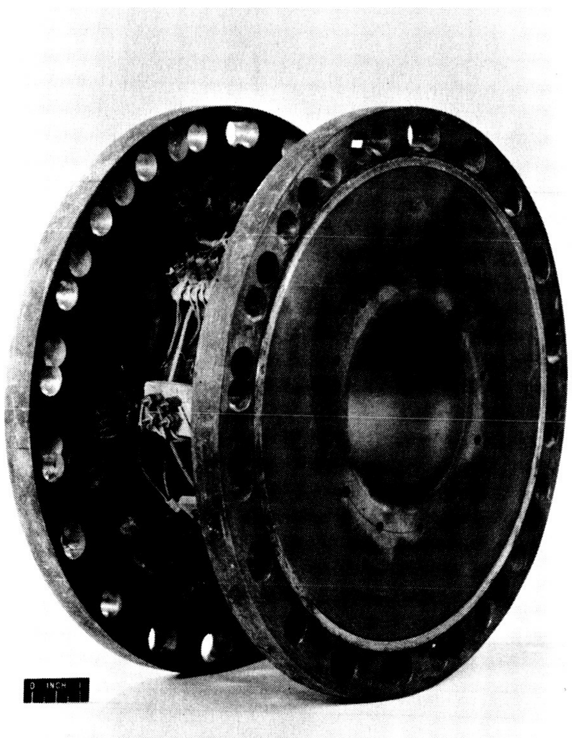


Figure 6. - Installation of thermocoupled rod used for measurement of one-dimensional heat-transfer.



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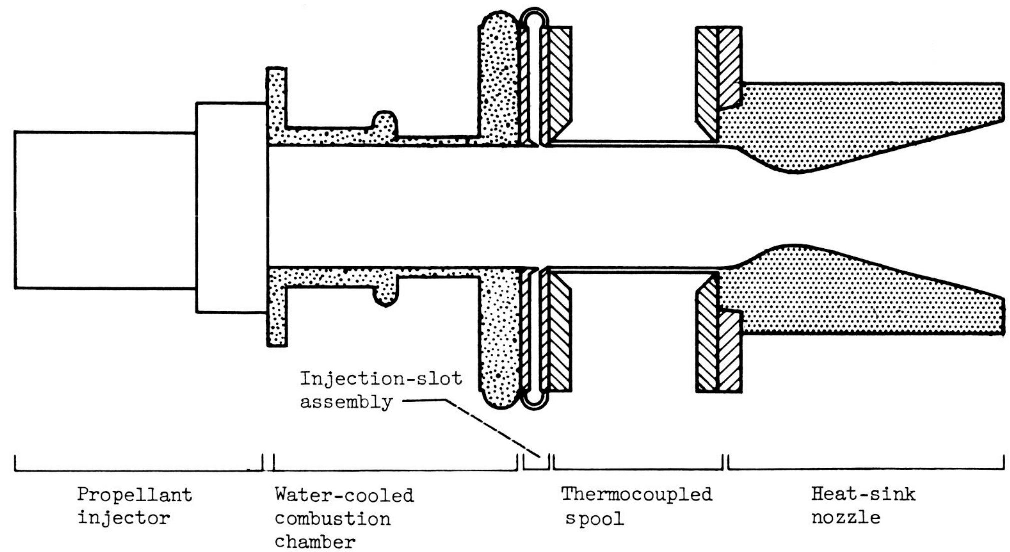
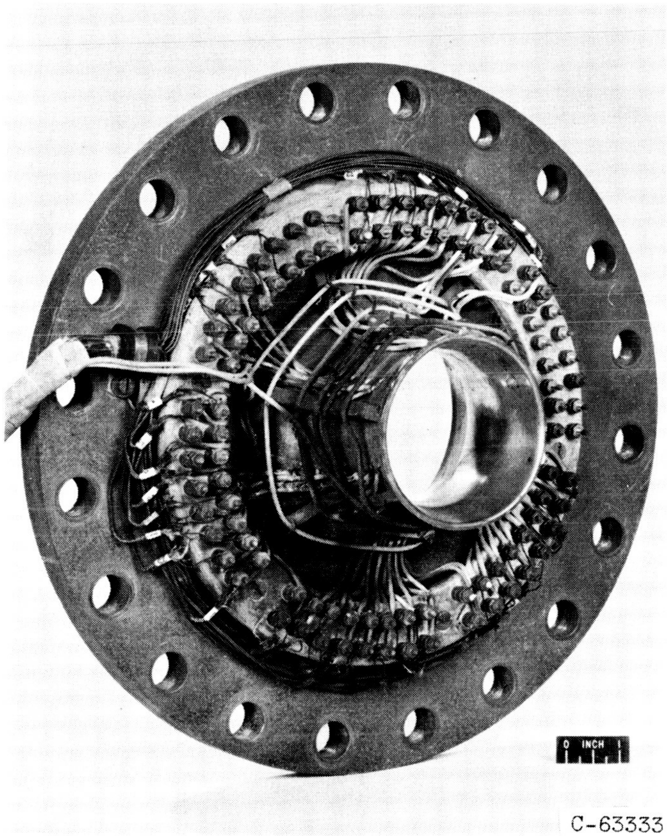


Figure 7. - Thin-wall spool with thermocouples and installation diagram.



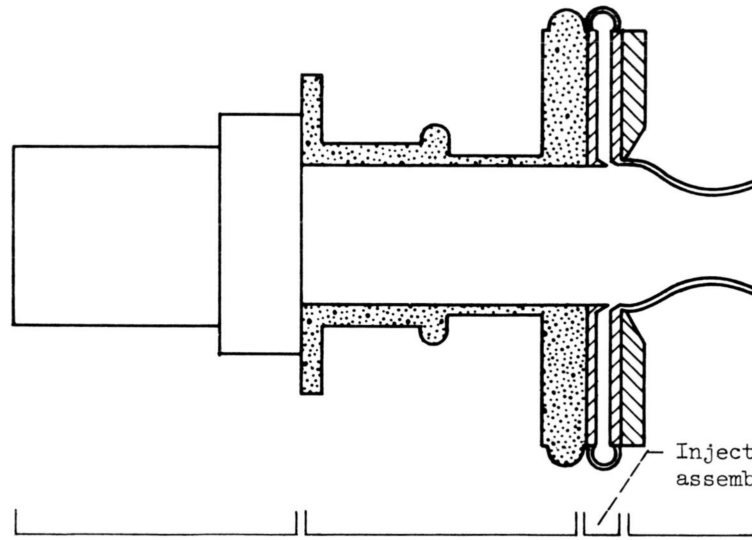


Figure 8. - Shortened thin-wall nozzle with thermocouples and installation diagram.

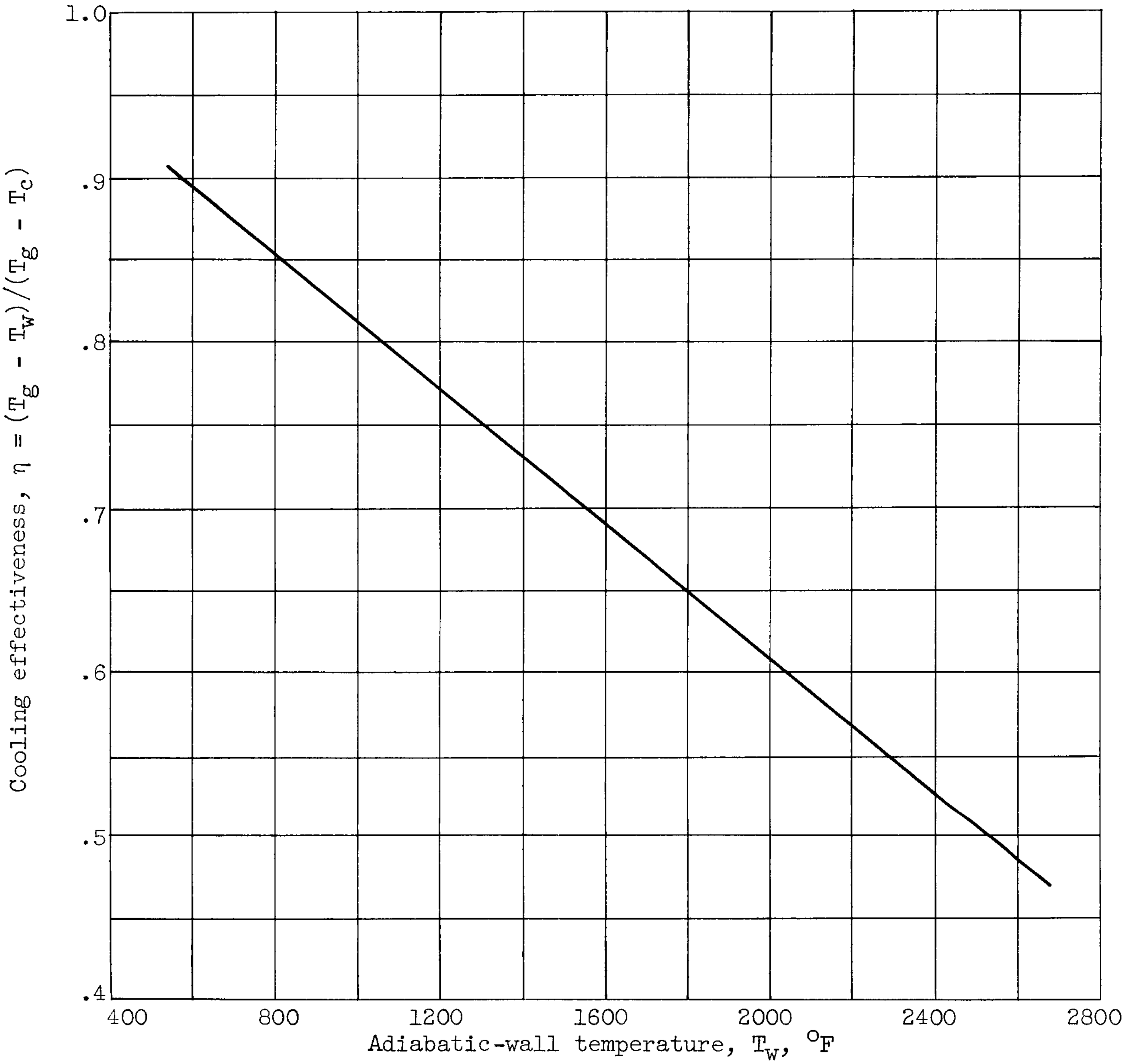


Figure 9. - Variation of cooling effectiveness with wall temperature. Hot-gas temperature, T_g, 5000° F; coolant temperature, T_c, 70° F.

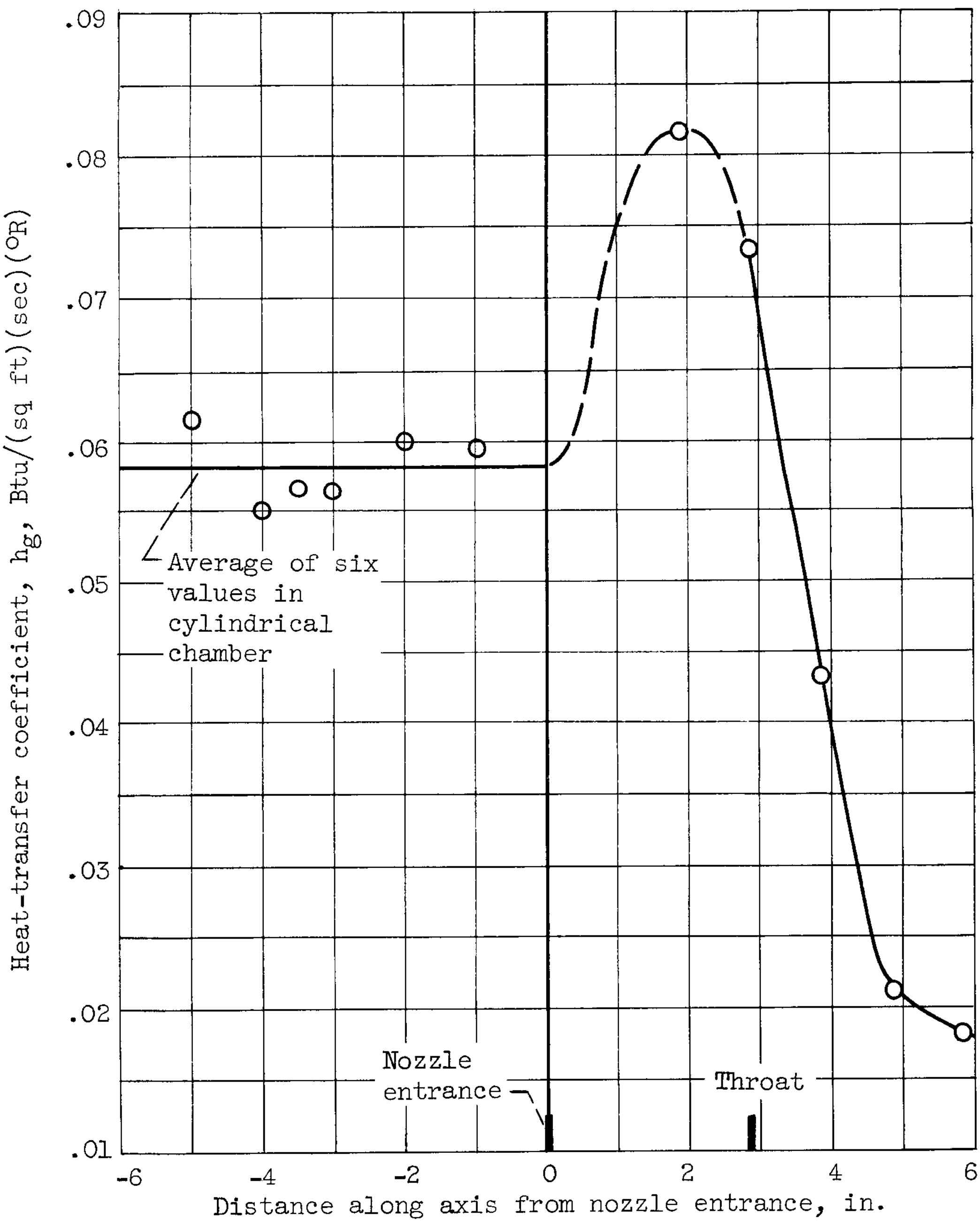


Figure 10. - Measured heat-transfer coefficients. Chamber pressure, 60 pounds per square inch absolute; stoichiometric mixture ratio.

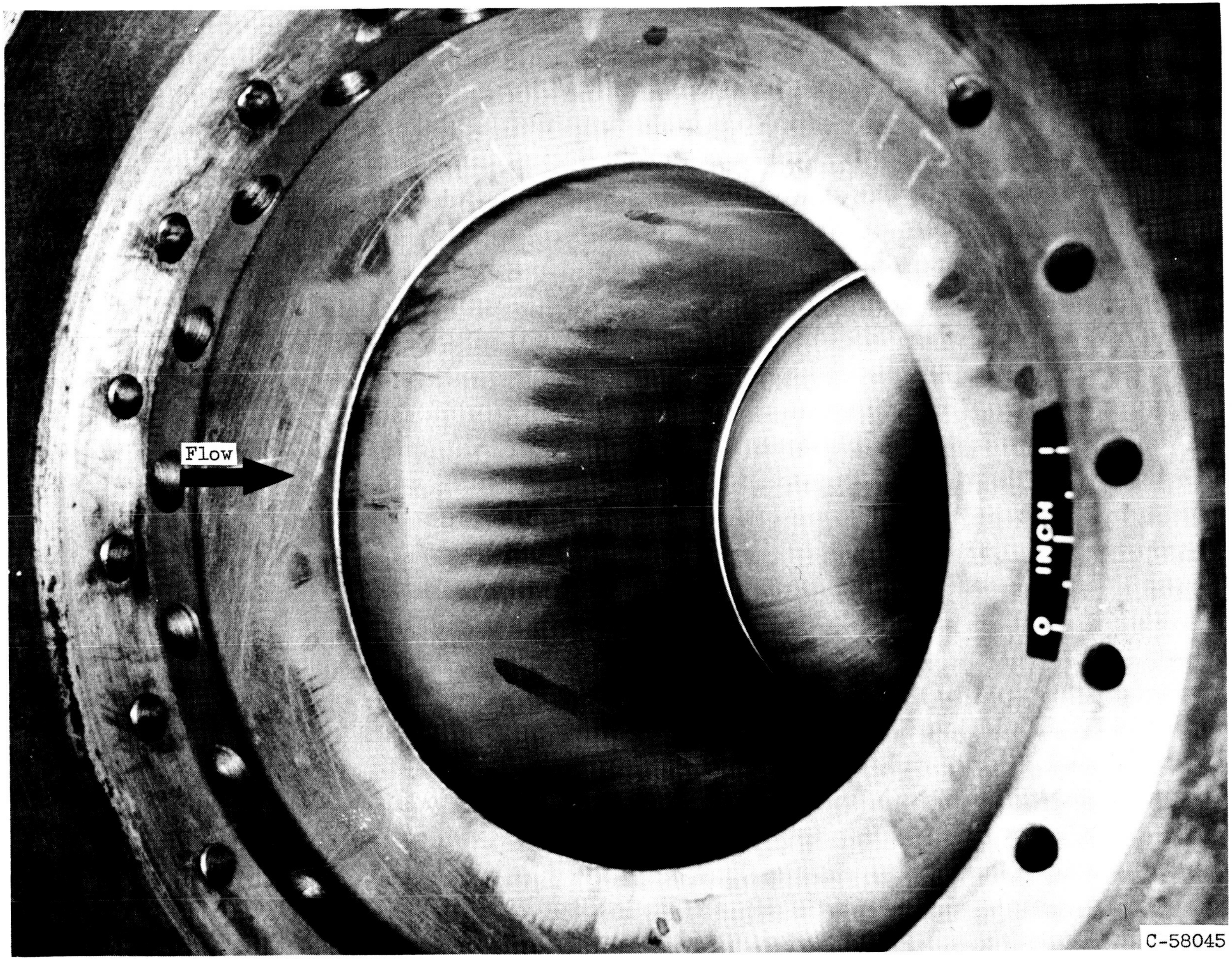
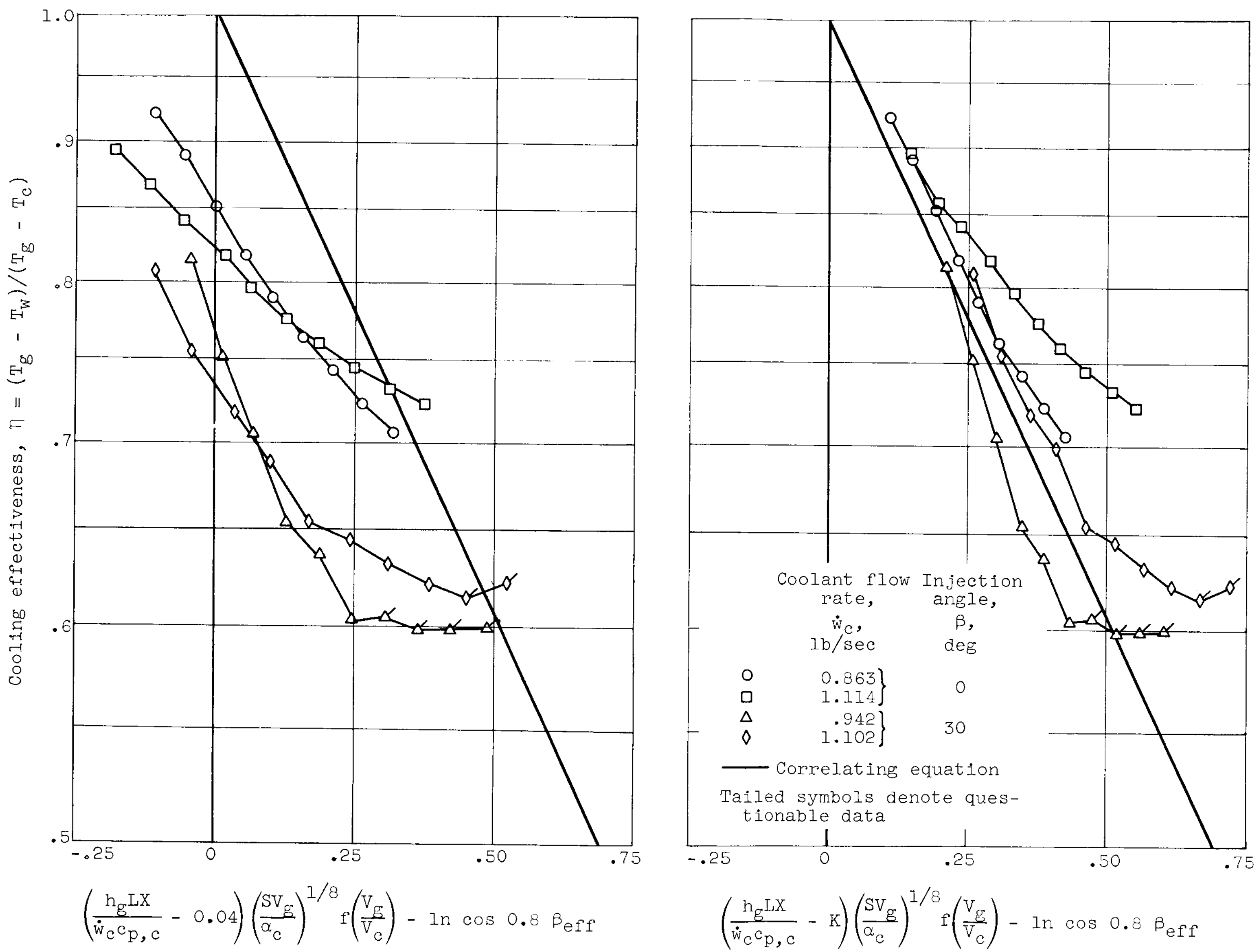


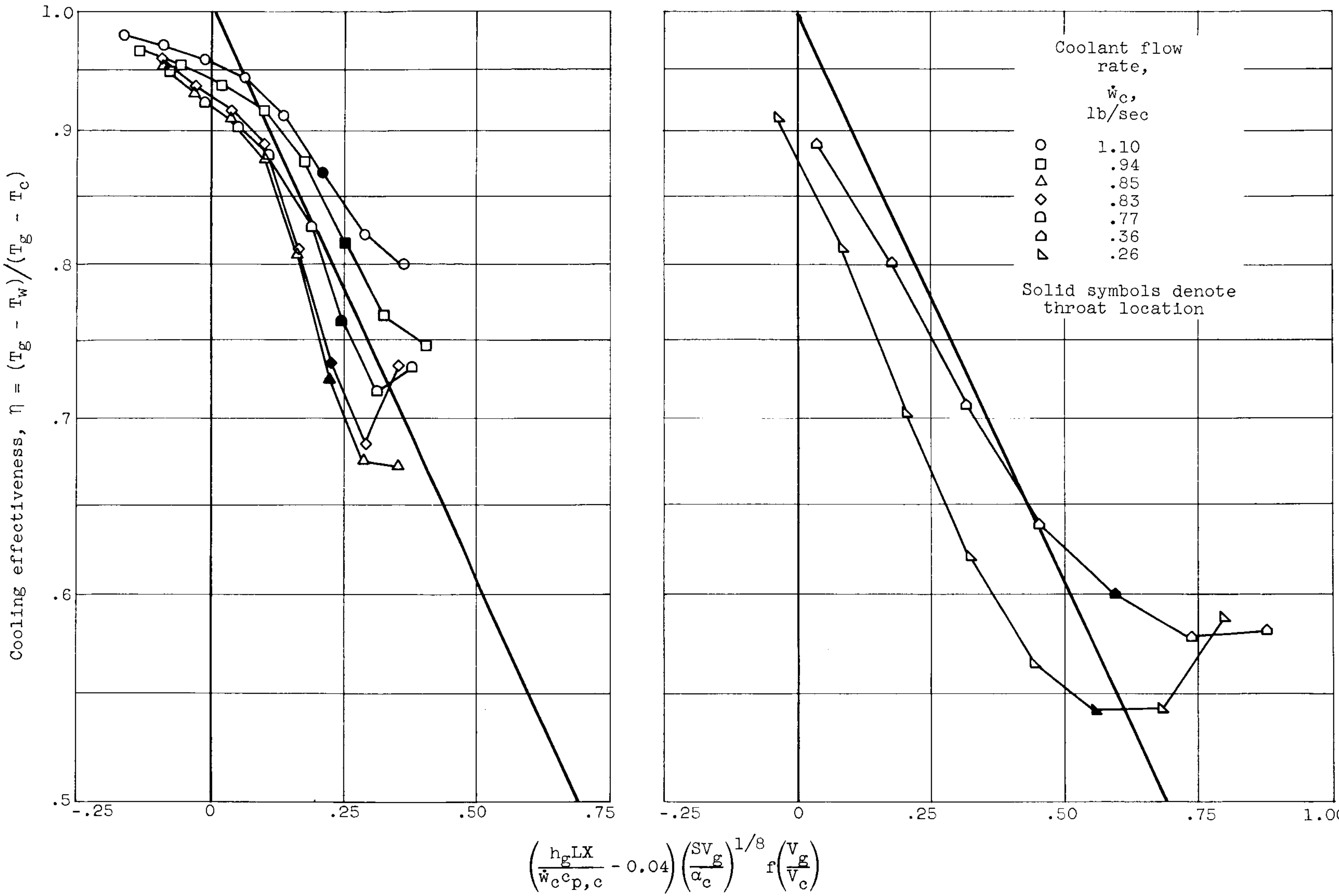
Figure 11. - Temperature discoloration pattern in thin-wall spool downstream of slot-lip supports.



(a) Correlation used as presented in references 5 and 6.

(b) Effect of changes of heat-transfer coefficient, and constant K in correlation.

Figure 12. - Effectiveness of cooling thin-wall spool with nitrogen as function of correlating parameter.



(a) Nitrogen coolant.

(b) Propane coolant.

Figure 13. - Effectiveness of cooling thin-wall nozzle as function of correlating parameter. Tangential injection.

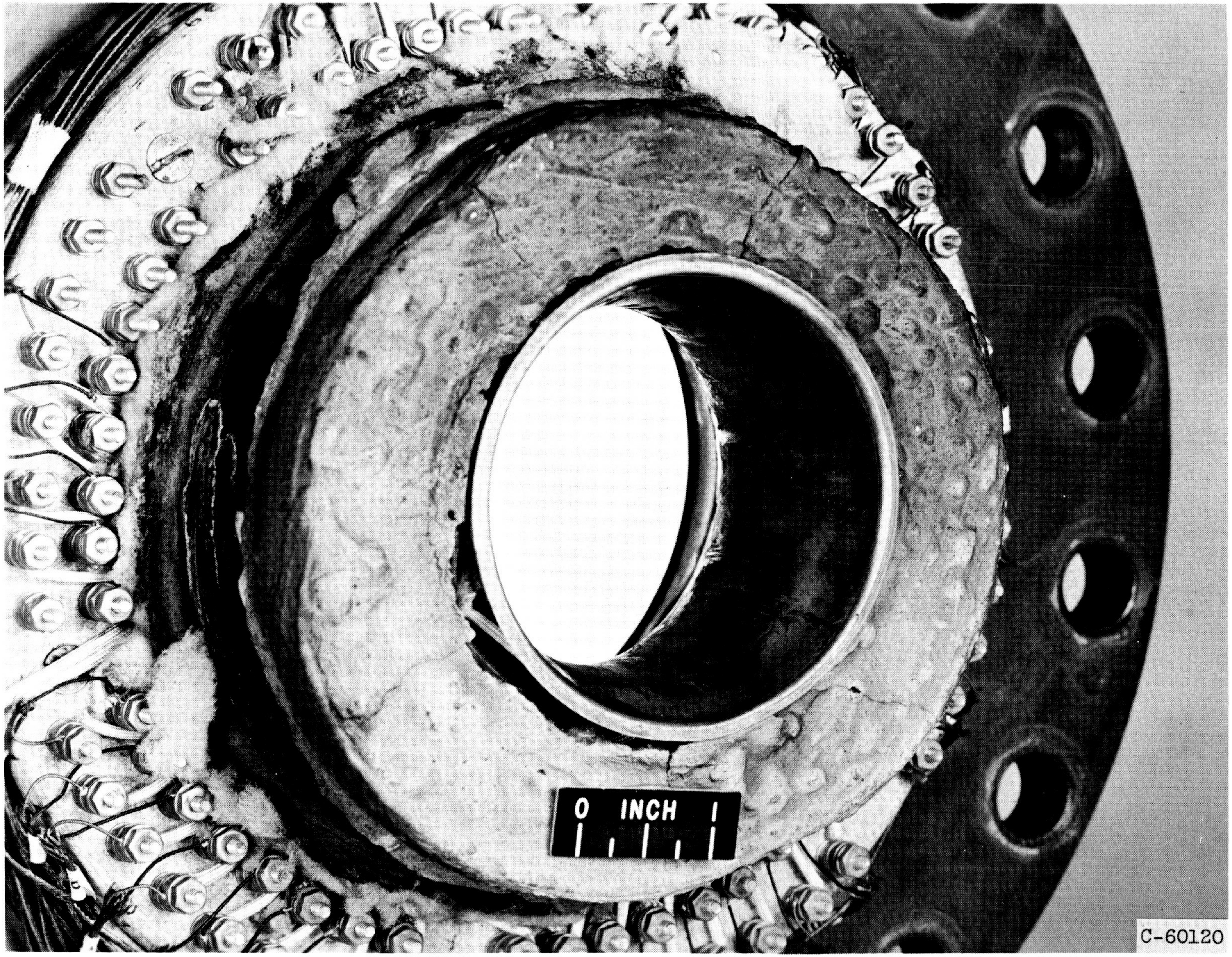


Figure 14. - Carbon deposition streaks in thin-wall nozzle after film cooling with propane gas.

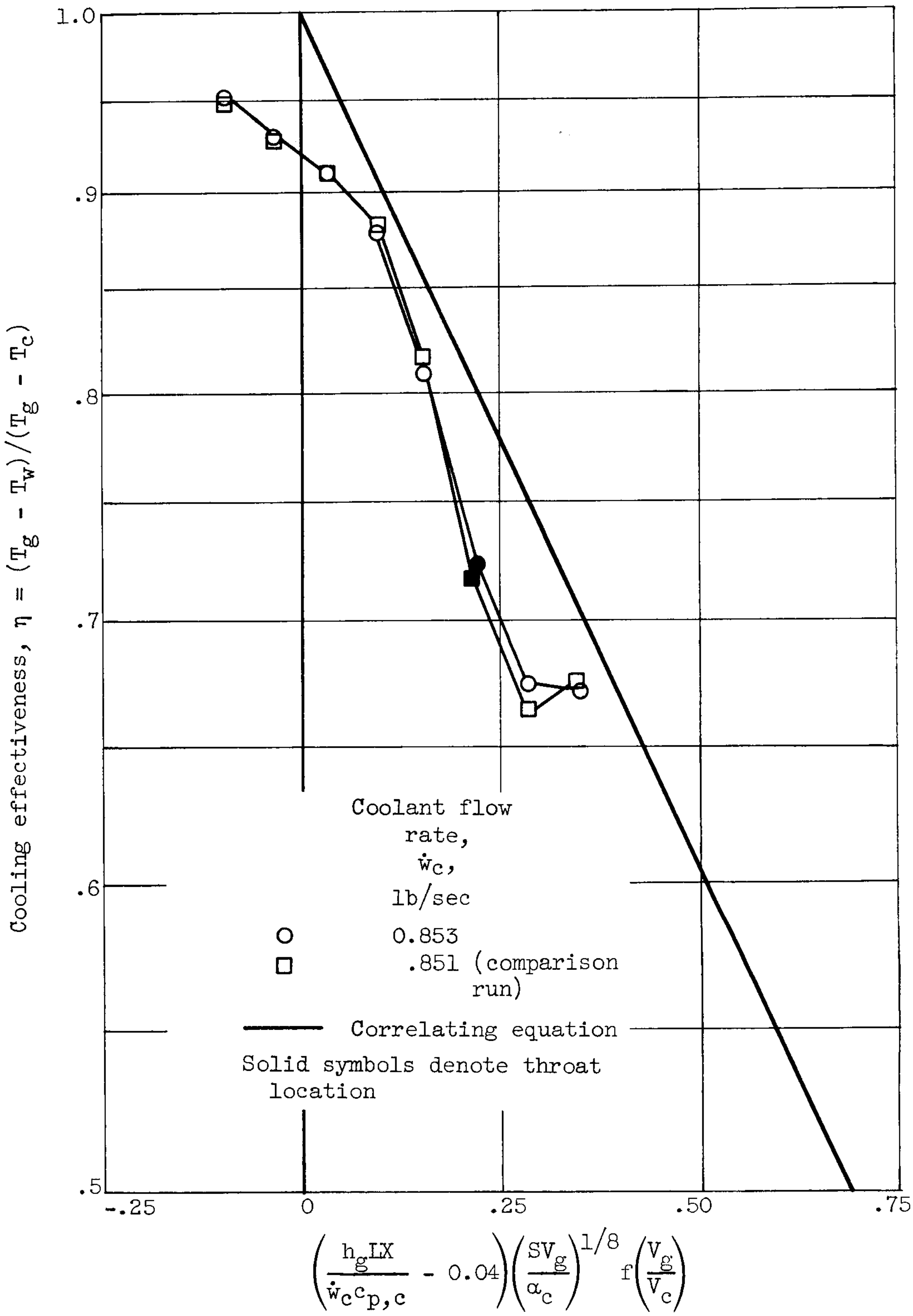


Figure 15. - Comparison runs to check reproducibility of data. Nitrogen-cooled thin-wall nozzle; tangential injection.

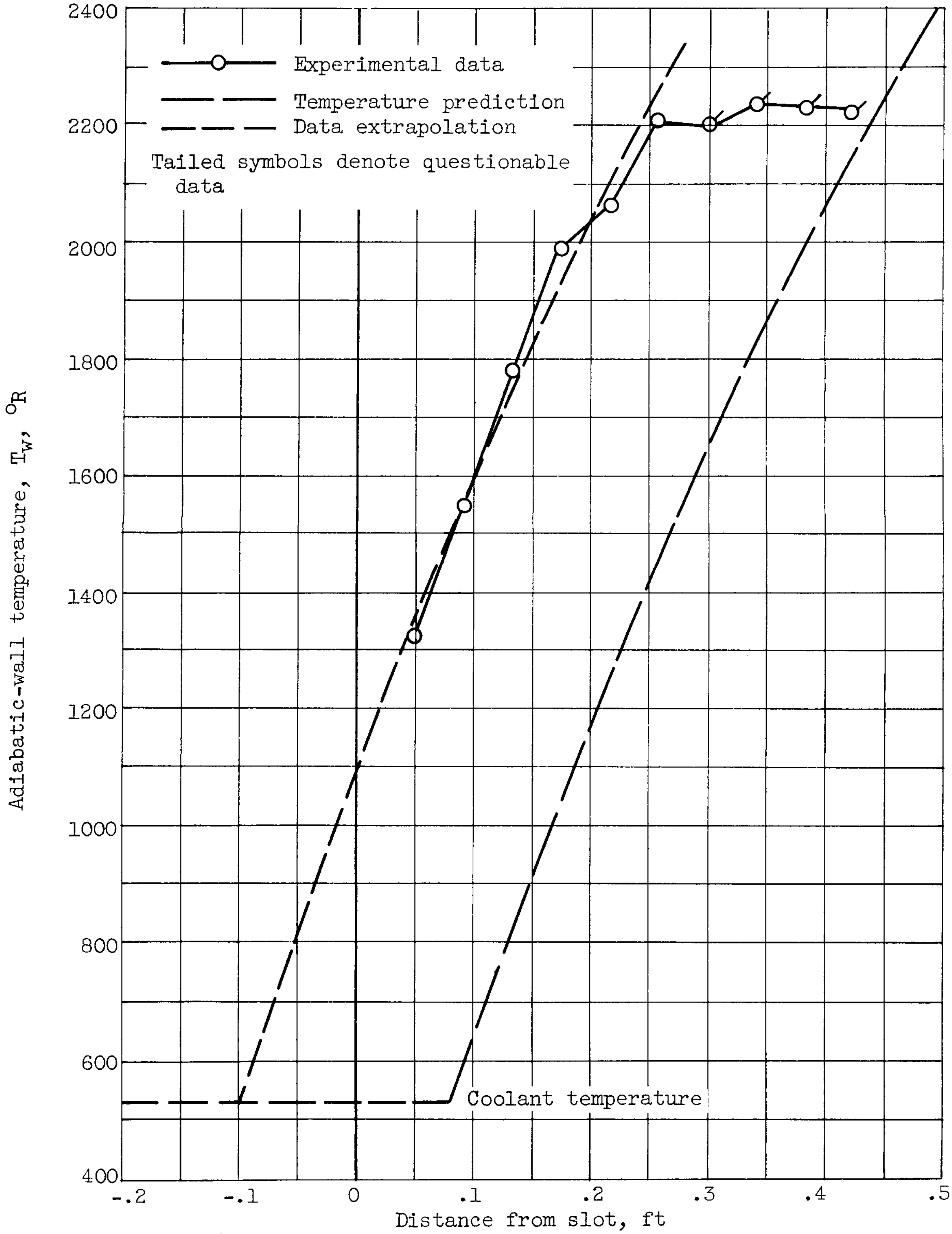


Figure 16. - Predicted and experimental adiabatic wall temperatures. Nitrogen coolant flow, 0.942 pound per second; injection angle, 30°.

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